Charm production in pA and *AA* collisions

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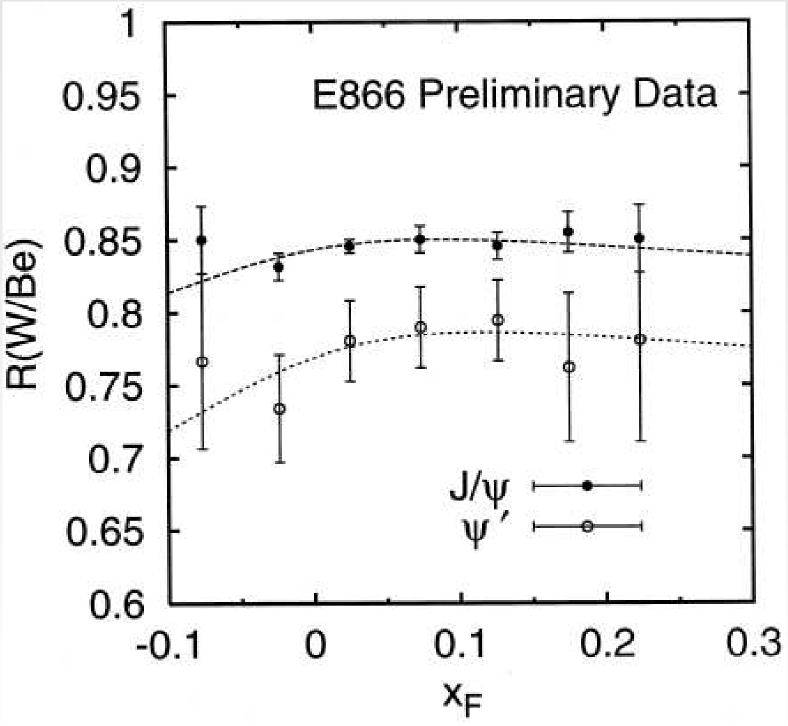
pA collisions at negative x_F

In pA collisions J/Ψ produced with $x_F < 0$ have low energy in the nuclear rest frame.

$$E_\Psi = \frac{m_\Psi^2 + \langle k_T^2 \rangle}{2 m_N |x_F|}$$

At low energy the color transparency effects are disappearing and absorption is getting stronger.

A stronger absorption of J/Ψ was predicted for negative x_F



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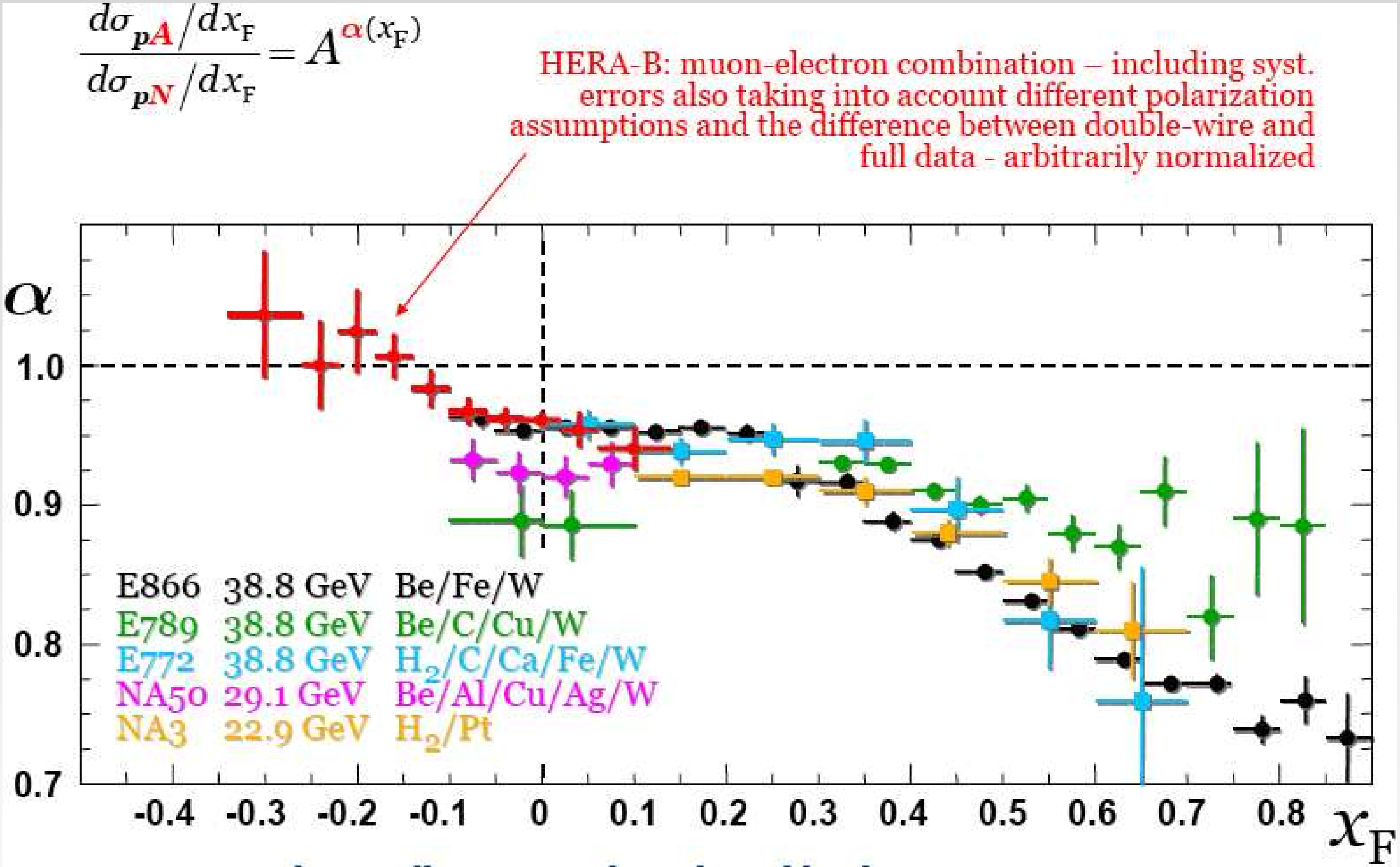
pA collisions at negative x_F

Quite a different behavior was observed in the HERA-B experiment recently



What is missing?

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Gluon cascading at negative x_F

Gluon radiation and particle production in multiple collisions is subject to Landau-Pomeranchuk suppression. Multiple interactions may not lead to multiple radiation, that is controlled by the coherence time of radiation,

$$t_c = \frac{2x_1 E}{M_T^2},$$

where $x_1 \ll 1$ is the fraction of the proton light-cone momentum carried by the radiated particle of mass M and transverse momentum k_T; $M_T^2 = M^2 + k_T^2$.

The first collision shakes off a part of the color field of the projectile (gluon bremsstrahlung), and it takes time t_c to restore the field. Only after that it can be shaken off once again.

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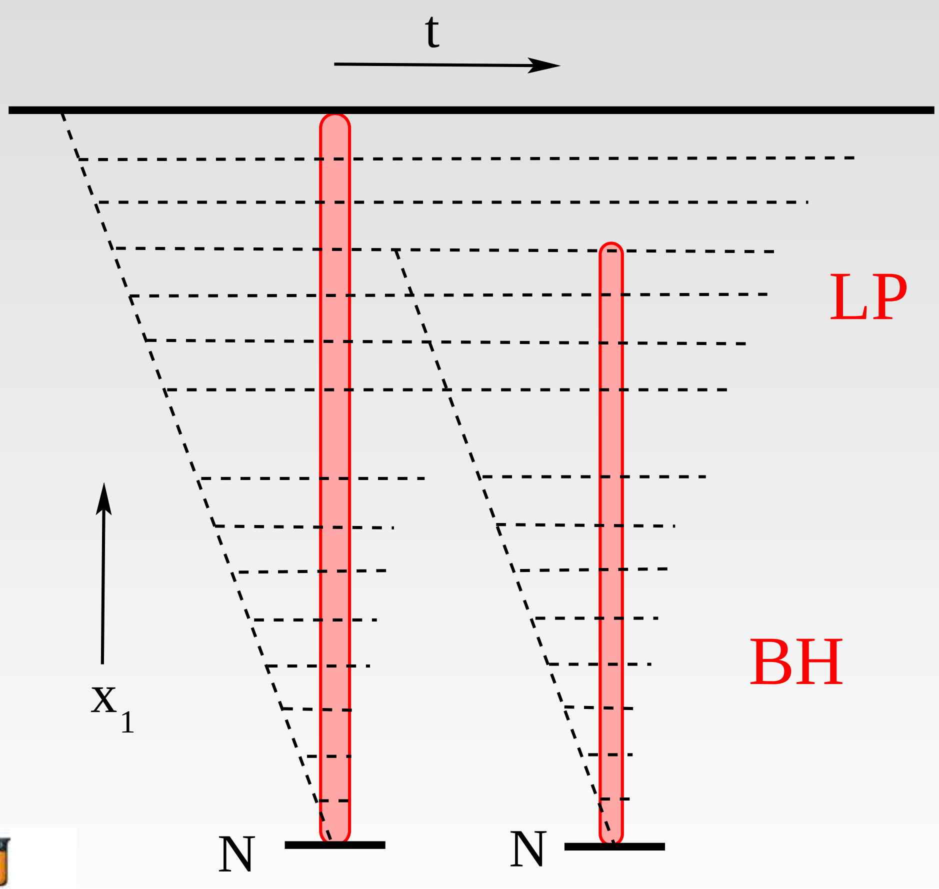
Gluon cascading at negative x_F

Thus, there two limiting regimes of bremsstrahlung from multiple interactions, coherent, Landau-Pomernchuk ($t_c \gg R_A$), and incoherent, Bethe-Heitler ($t_c \ll R_A$) regimes of radiation.



Thus, cascading increases particle multiplicity in the nuclear fragmentation region, especially for particles produced in hard reactions (J/Ψ, $\bar{c}c$, high-p_T, etc.), which have shorter coherence time.

- A similar phenomenon occurs in the string model.

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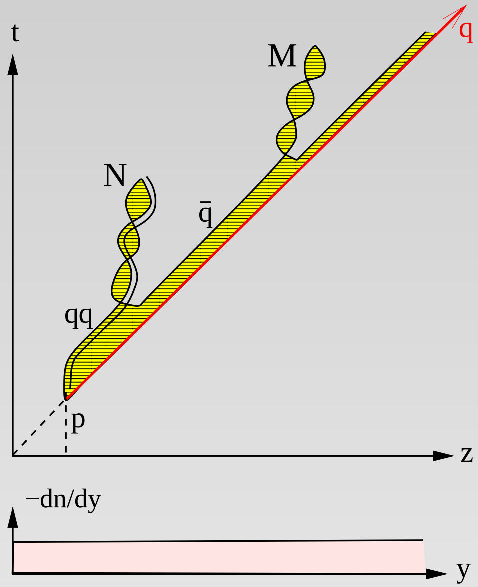
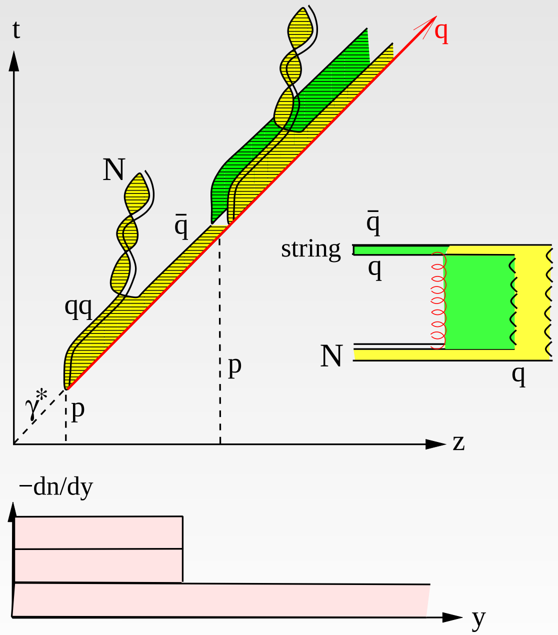
Cascading of strings

If a quark is knocked out of a proton in a hard reaction a heavy quark-diquark string is formed and propagates near the light cone decaying via tunneling of $\bar{q}q$ pairs from vacuum. Mesons are produced with momenta ordering in a geometrical progression, i.e. they form a plateau in rapidity.



If the string interacts with another bound nucleon, two new strings, light and heavy ones, are produced. As a result, a plato of triple hight is produced in the nuclear fragmentation region $\Delta y \sim \ln(\kappa R_A)$.



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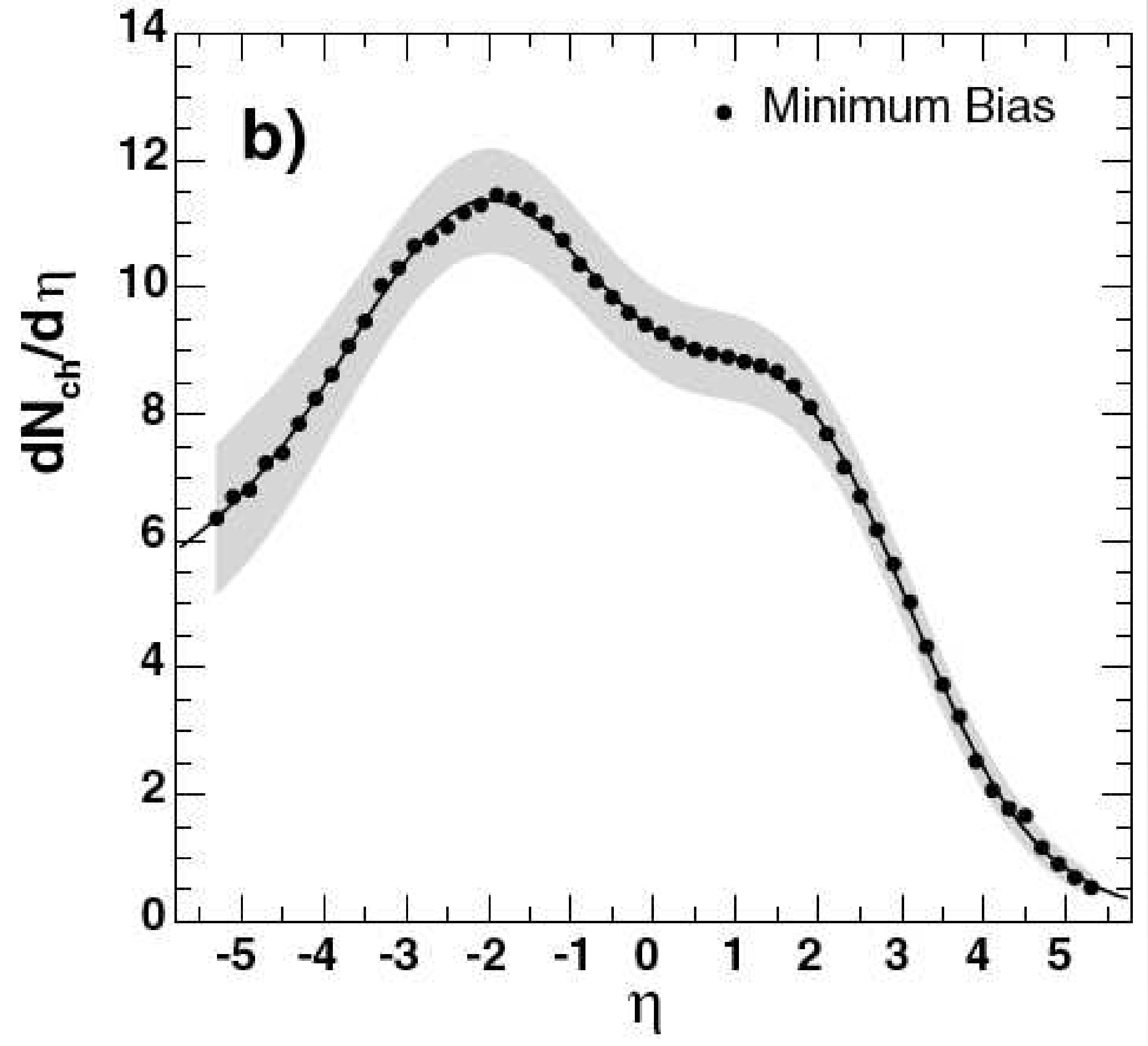
Gluon cascading at negative x_F

Gluon cascading in the nuclear fragmentation region can be observed in the inclusive cross section of hadron production in pA collisions.

PHOBOS data for dA collisions at $\sqrt{s} = 200\,\text{GeV}$



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Gluon cascading at negative x_F

A gluon (photon) with $t_c \gg R_A$ cannot be radiated twice in spite of multiple interactions of its source (only $\langle p_T^2 \rangle$ increases). However, gluons with $t_c \ll R_A$ can be radiated multiply.

At high energies and negative finite $|x_F| \gg M_T^2/s$,

$$x_1 = \frac{M_T^2}{|x_F|s}$$

So, $$t_c = \frac{1}{|x_F| m_N}$$ (only for finite negative x_F)

The radiation time at $x_F < 0$ turns out to be independent of what is radiated and it scales in x_F. Correspondingly, the nuclear effects at fixed negative $x_F < 0$ should be independent of energy.

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Gluon cascading at negative x_F

The border line between coherent and incoherent regimes of radiation is the radiation time of the order of the internucleon spacing, $\Delta \approx 2\,\mathrm{fm}$,

$$x_F^0 = -\frac{1}{m_N \Delta} \approx -0.1$$

- At $x_F > x_F^0$ radiation from multiple interactions is coherent, Landau-Pomeranchuk regime.

- At $x_F < x_F^0$ the Bethe-Heitler regime of radiation takes over. Every multiple interaction contributes to the radiation spectrum incoherently.

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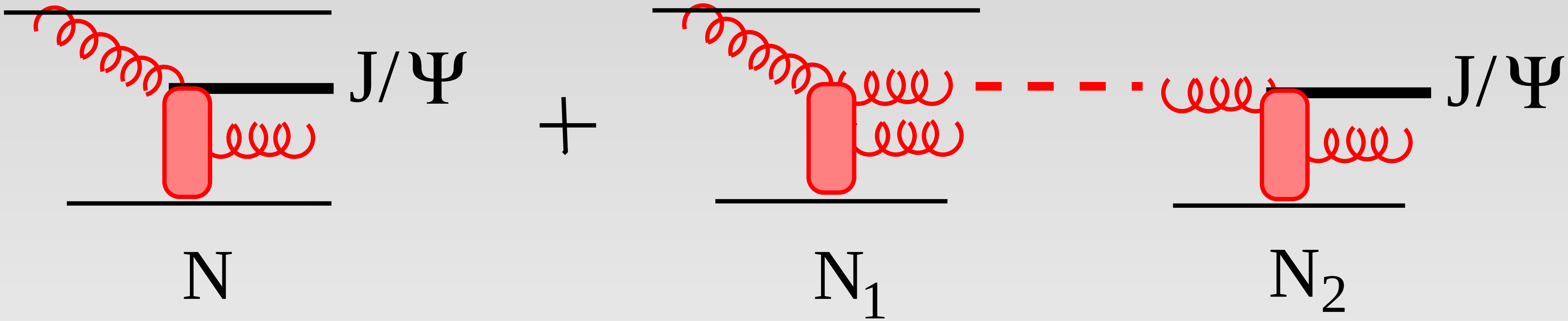
J/Ψ production at $x_F < x_F^0$

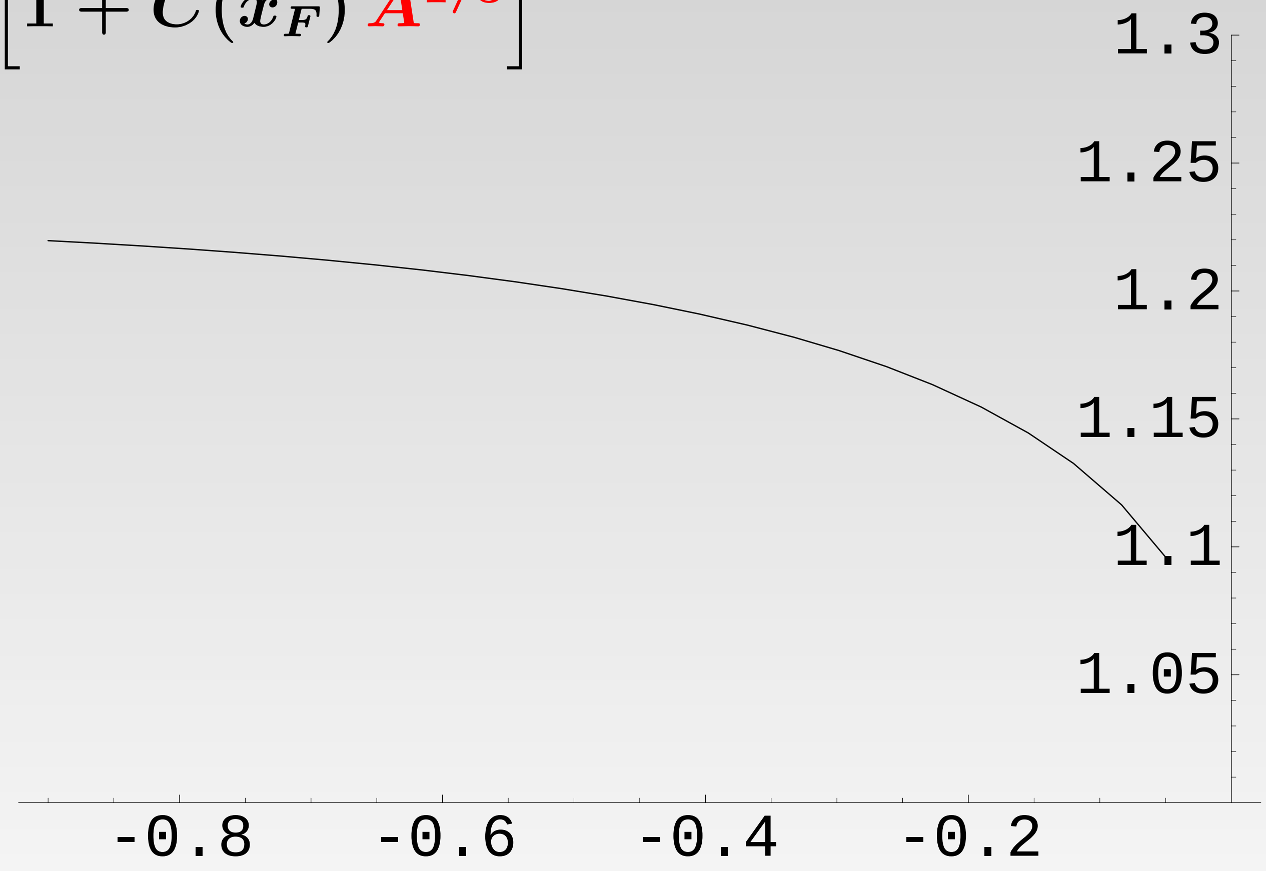
In the Bethe-Heitler regime gluons radiated in the first collision can produce J/Ψ on another nucleon.



$$\frac{d\sigma^{NA}_{J/\Psi}}{dx_1 d^2b} = f_g^N(x_1)\,\sigma^{gN}_{J/\Psi}\,T_A(b) + \\ + \frac{1}{2}\sigma^{gN}_{J/\Psi}\int d^2p_T\Big[T_A(b) - l_c(p_T)\Big]^2 \frac{d\sigma_g^{NN}}{dx_1 d^2p_T}$$

J/Ψ production at $x_F < x_F^0$

Thus, J/Ψ production at $x_F < 1$ is enhanced by the factor $\left[1 + C(x_F)\, A^{1/3}\right]$



About 20% effect is expected, same for J/Ψ, charm, high-p_T, and any hard reaction. The effect scales in x_F.

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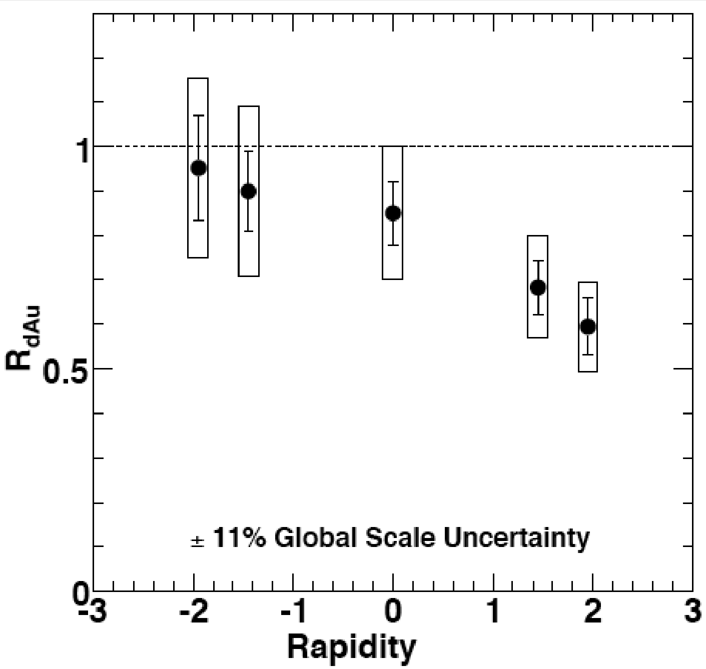
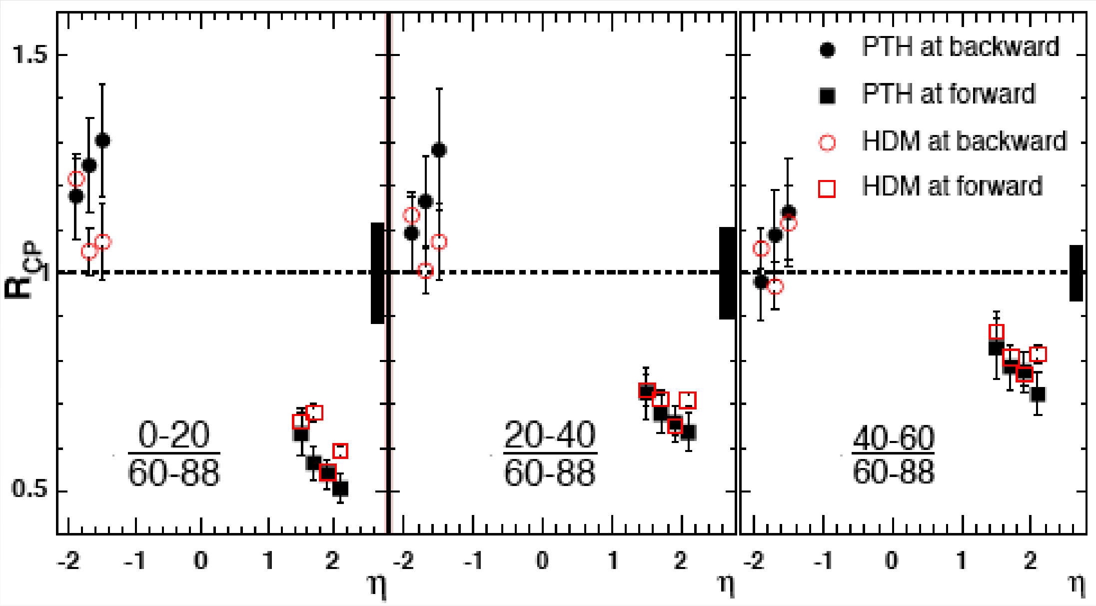
J/Ψ production at $x_F < x_F^0$

PHENIX results for J/Ψ and high-p_T hadron production versus rapidity confirm universality of the enhancement at $x_F < 0$.

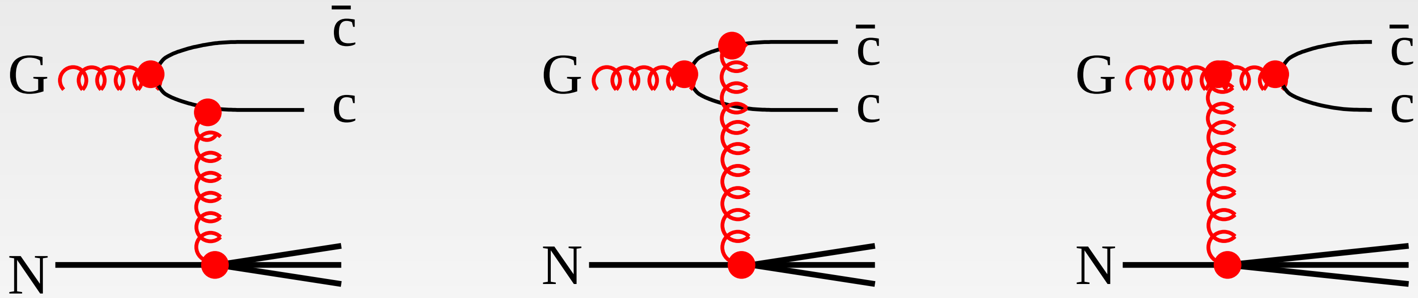




Shadowing at $x_F > 0$

This region of coherent gluon radiation is fully controlled by the Landau-Pomeranchuk effect which leads to leading twist shadowing. Gluon shadowing depends logarithmically on the hard scale.

Higher twist shadowing is related to a nonzero $\bar{Q}Q$ separation. It causes a suppression which vanishes with the heavy quark mass as $1/m_Q^2$. In terms of the parton model this is shadowing of heavy quarks.



When the $\bar{c}c$ transverse separation vanishes, $r_T \to 0$, the three graphs cancel each other.

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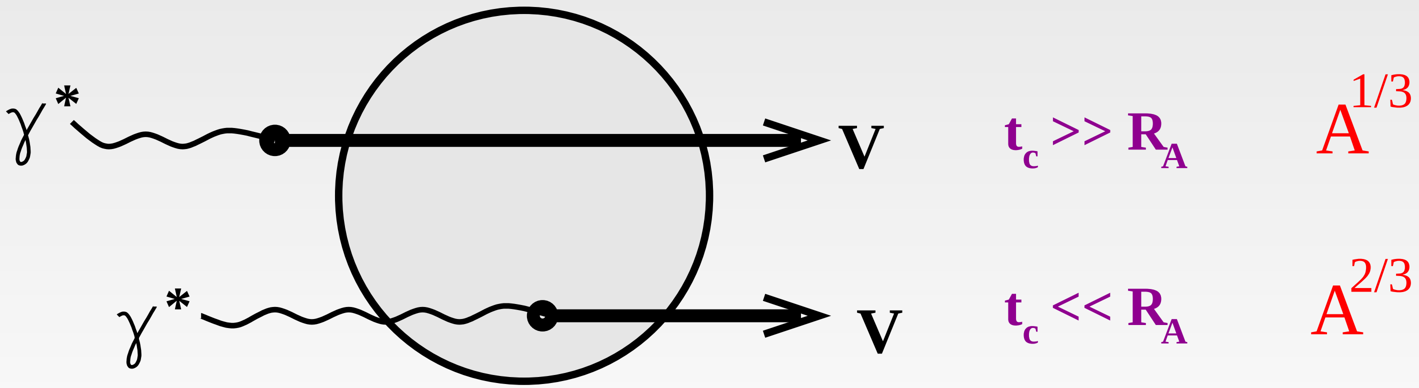
Shadowing at $x_F > 0$

• In the case of charmonium production one should discriminate between quark shadowing and absorption, which is also a higher twist effect. The interplay of the two sources of suppression is controlled by coherence. Apparently, open heavy flavor production is subject to shadowing only.

Simple analogy:



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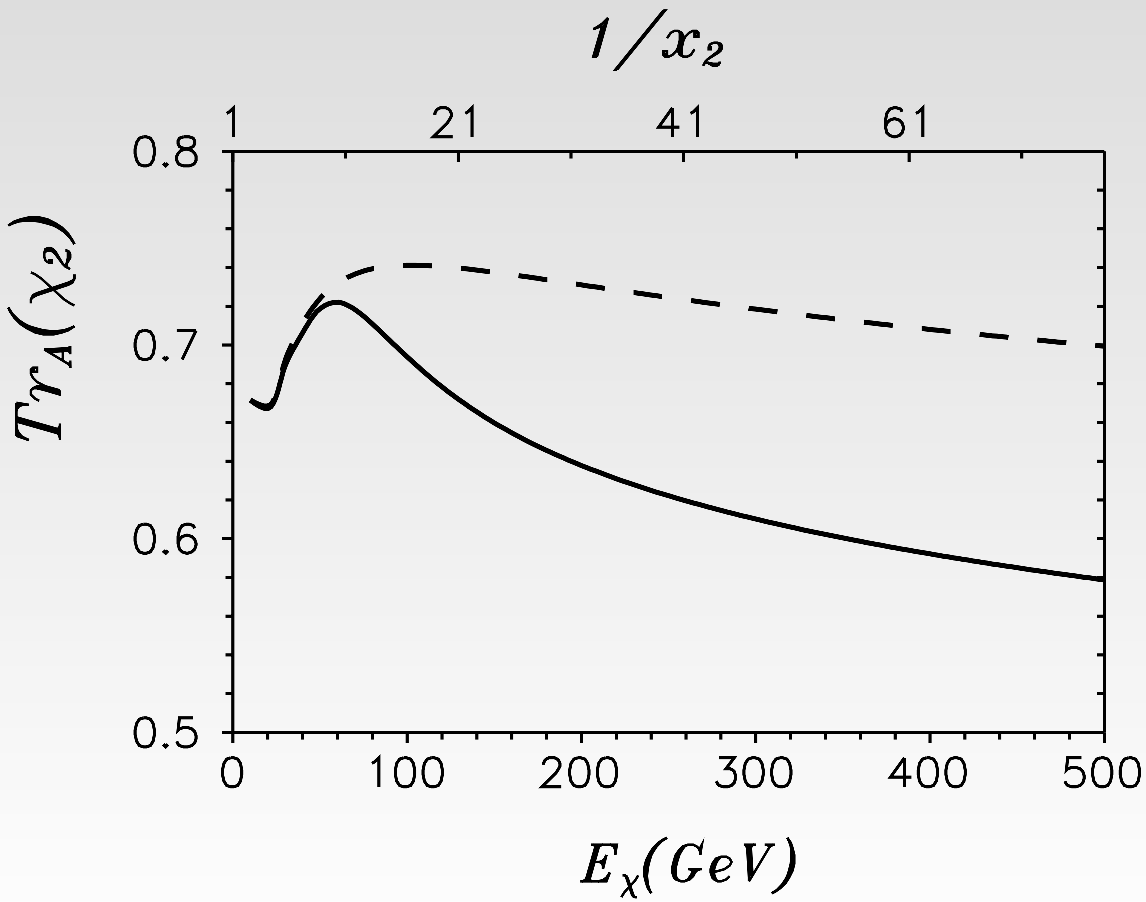
Shadowing for charmonium

Higher twist quark shadowing is appreciable for charmonium due to a large size. It was calculated for χ_2 which has a simple production mechanism.

$E_\chi = M_T^2/(2m_N x_2)$, so the charmonium energy depends only on x_2. Therefore nuclear effect scale in x_2.

Dashed: absorption, no shadowing

Solid: higher twist shadowing is added



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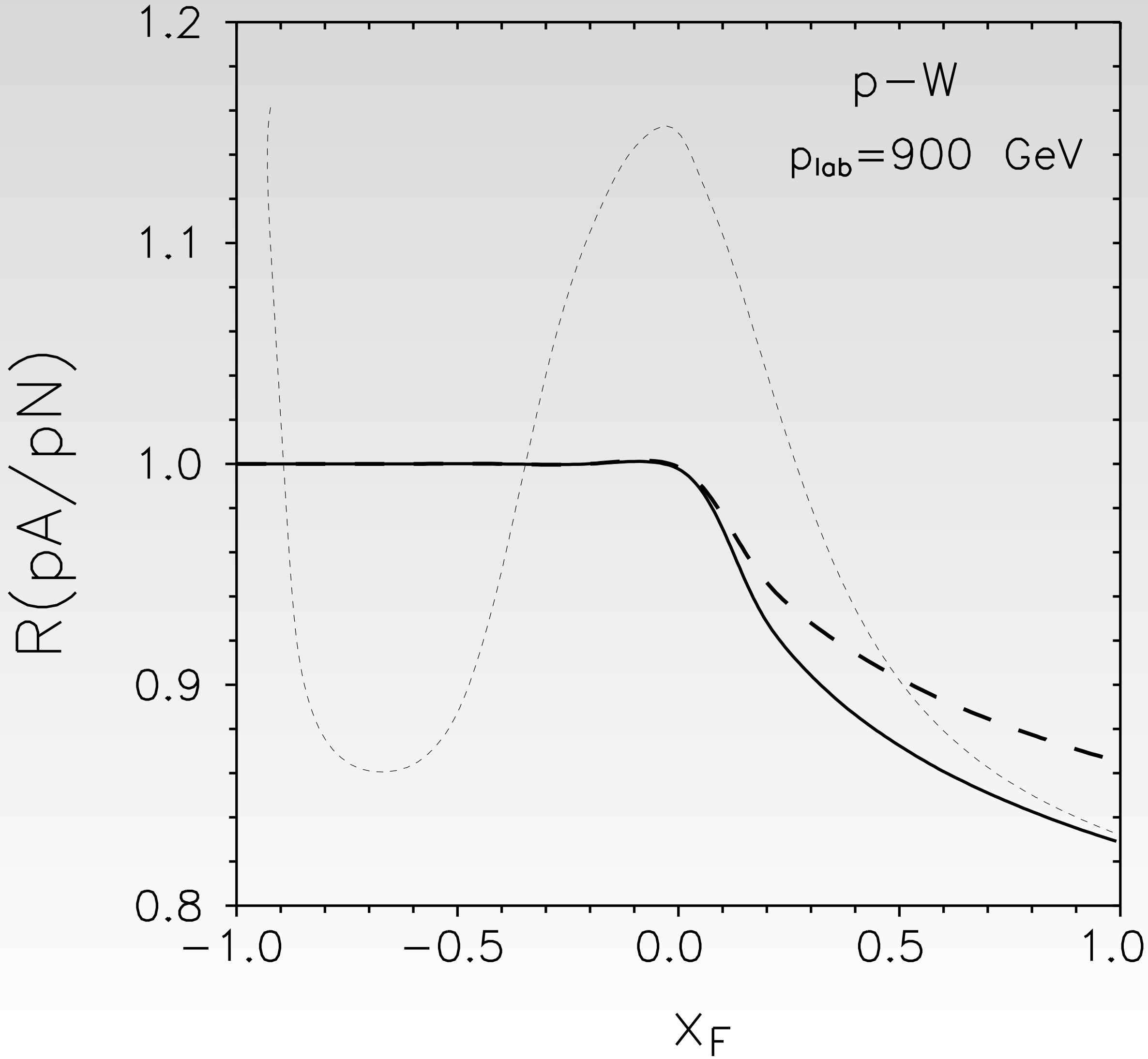
Shadowing for open charm

Charm is less suppressed, since the $\bar{c}c$ separation is smaller.



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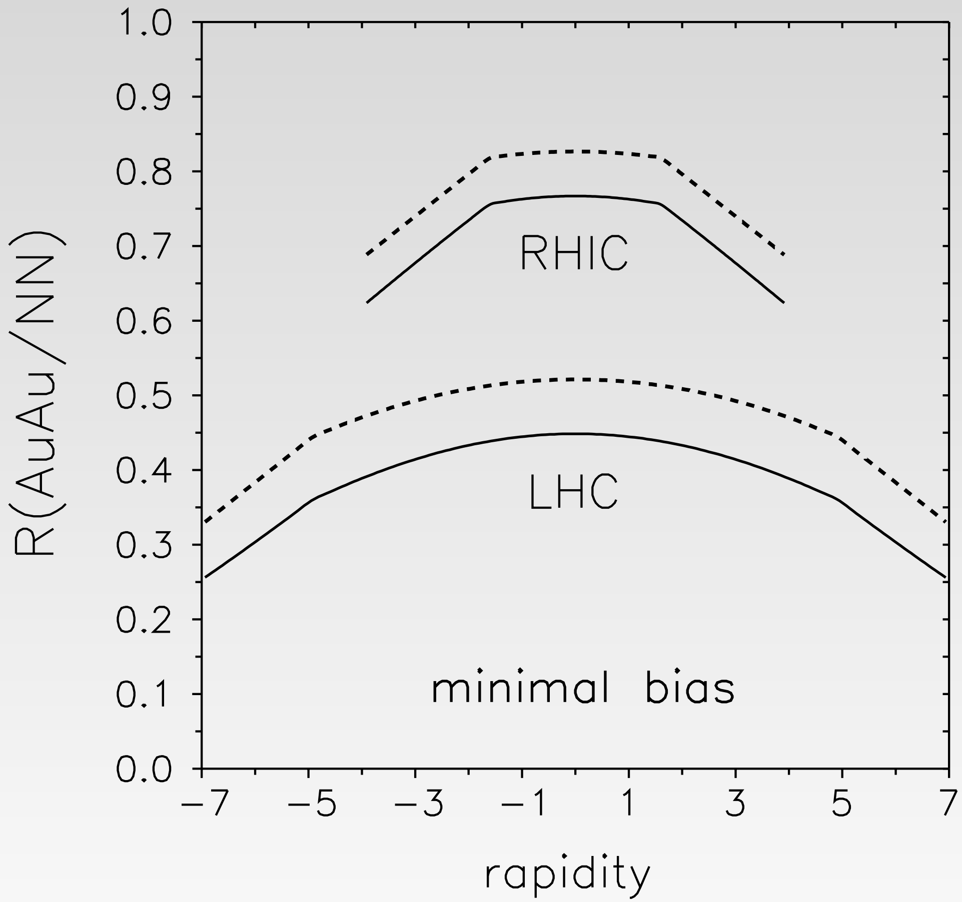
Shadowing for open charm

Nuclear shadowing for open charm production in minimal bias gold-gold collision. Dotted curves correspond to net effect of gluon shadowing, while solid curves include both effects of gluon shadowing and the higher twist correction related to the nonzero separation of the $\bar{c}c$. The top (RHIC) and bottom (LHC) curves correspond to $\sqrt{s} = 200\,\mathrm{GeV}$ and $5500\,\mathrm{GeV}$ respectively.



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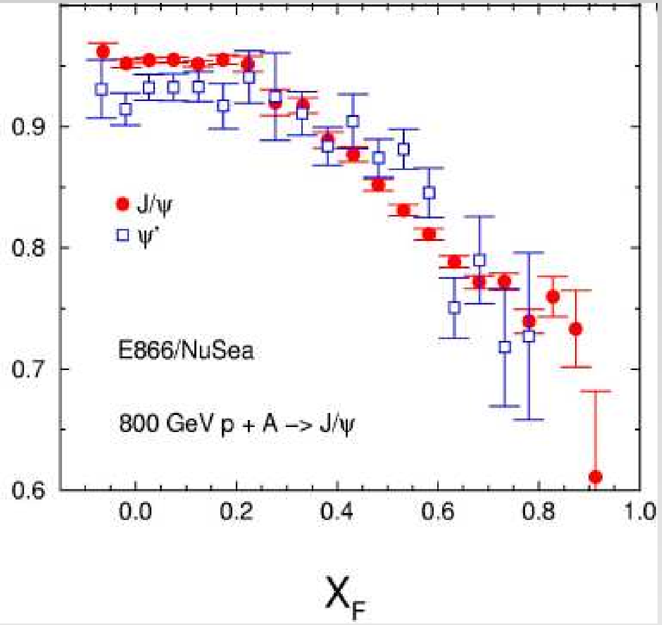
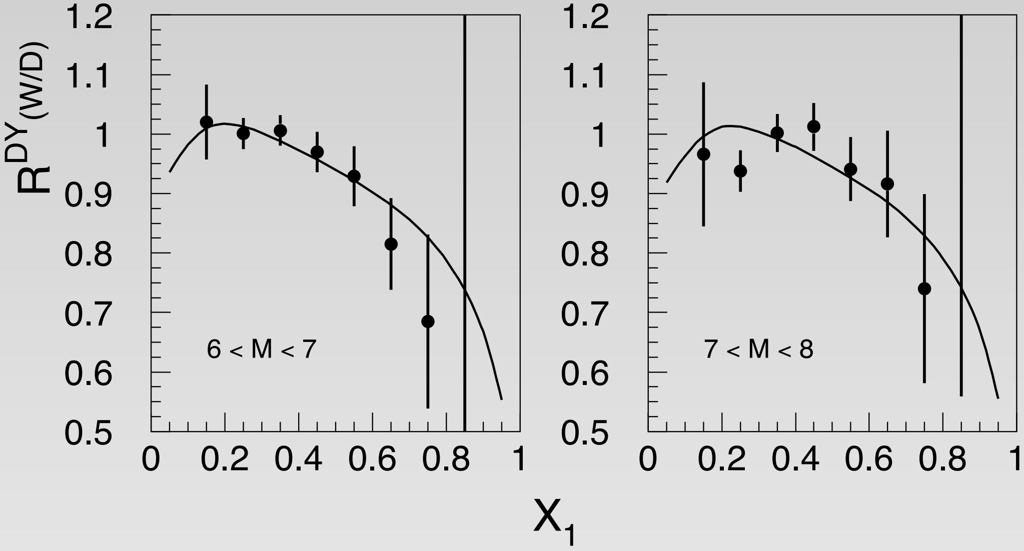
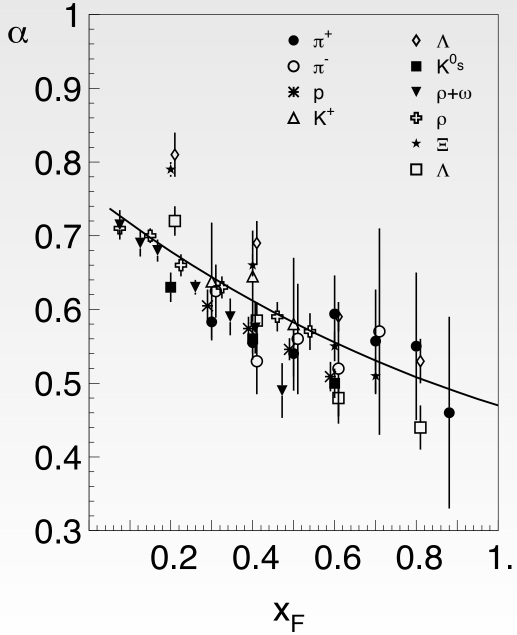
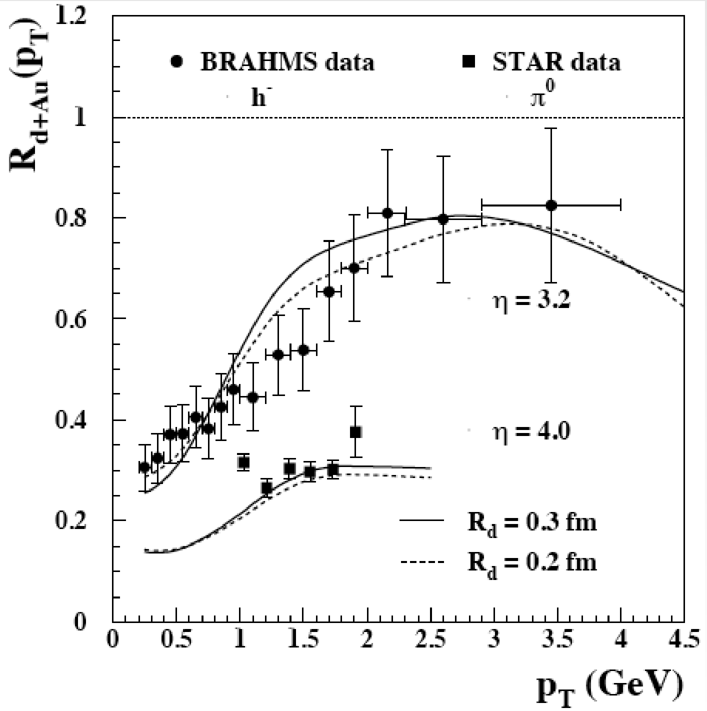
Suppression at large x_F









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Suppression of forward J/Ψs

It turns out that all measured so far reaction (soft and hard, and low and high energies) shows an enhanced nuclear suppression towards the kinematic limit, e.g. large $x_F \to 1$. Moreover, x_F scaling is observed wherever data allow to test it.

- There might be a common reason for that: Nuclei compared to a proton target enhance the contribution of higher Fock components, since each parton has a good chance to interact. These multi-parton Fock states have to share the energy between the partons, so the chance for one parton to grab the whole energy is reduced.

Apparently, such a suppression is subject to x_1 scaling, which is same as x_F scaling at large x_1.

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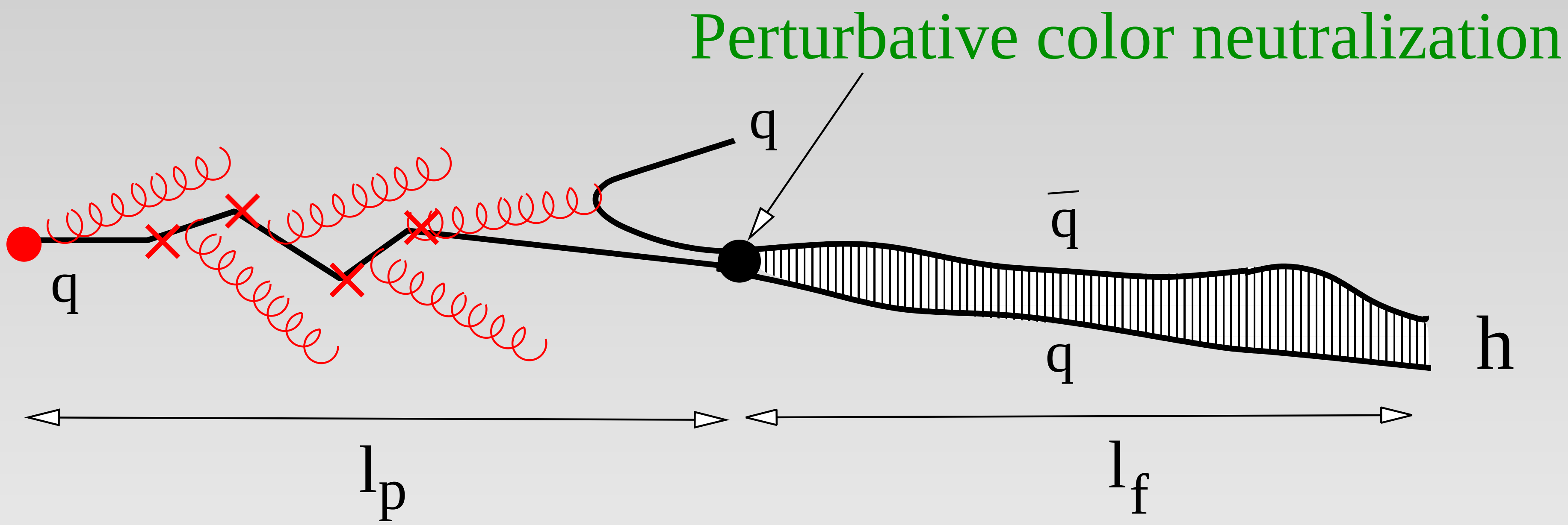
Perturbative hadronization



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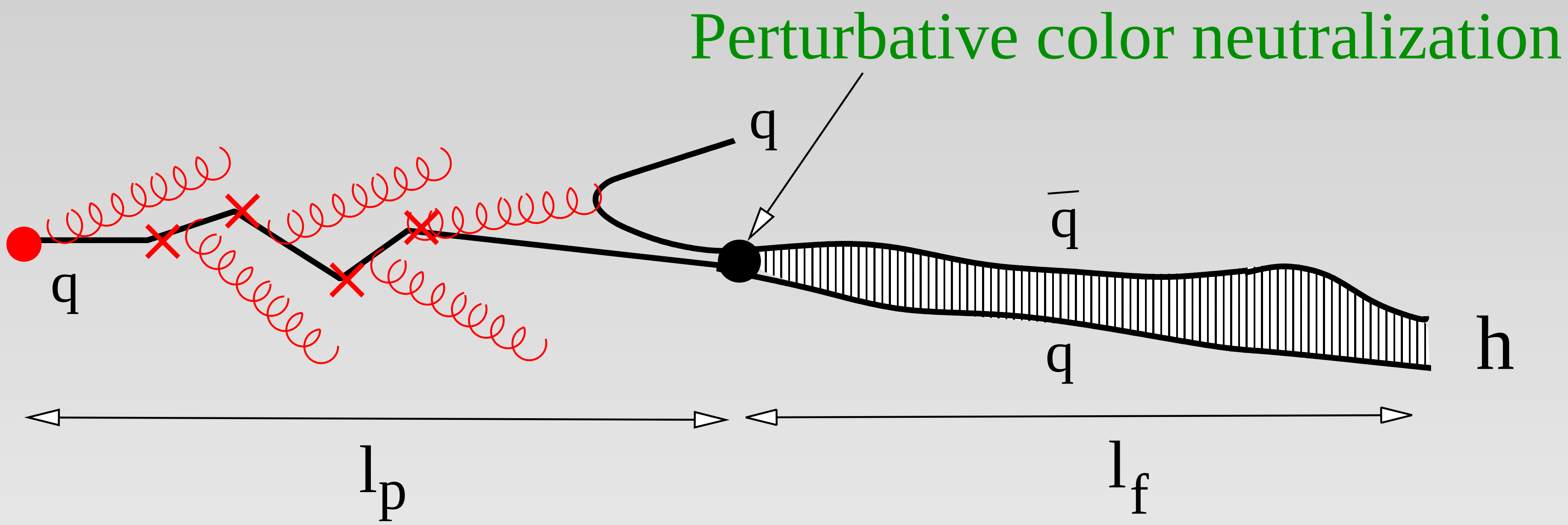

Two sources of hadron quenching:

(i) energy loss of the parton prior production of a pre-hadron;

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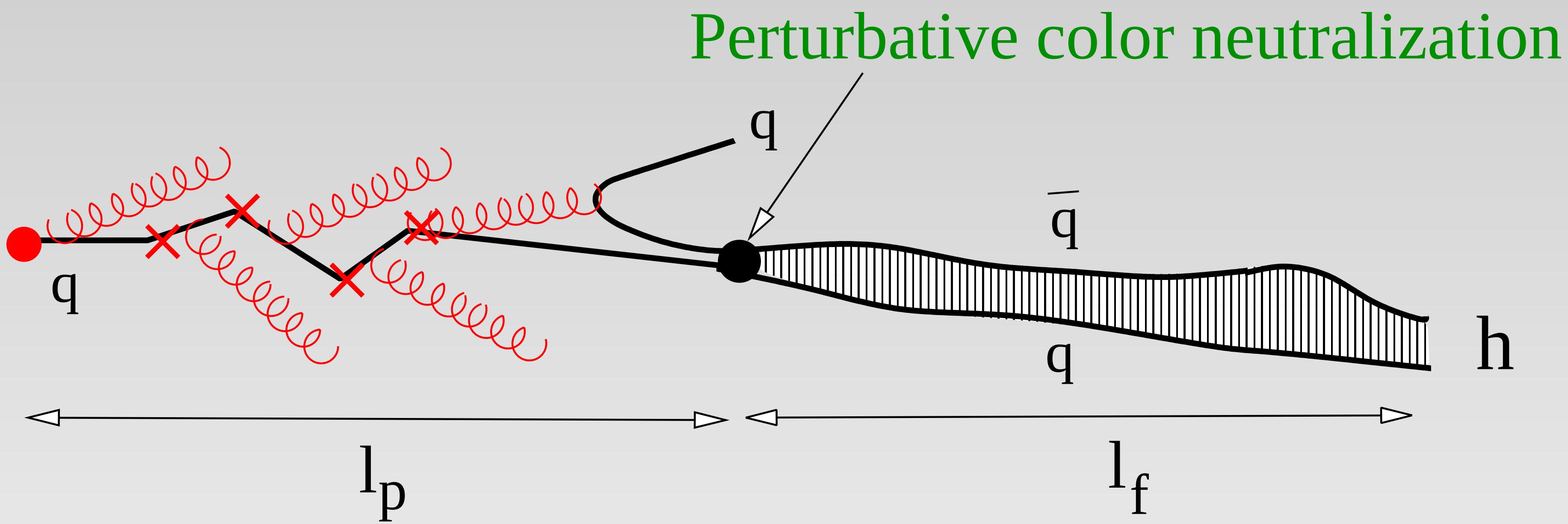
Perturbative hadronization



Two sources of hadron quenching:

(i) energy loss of the parton prior production of a pre-hadron;

(ii) attenuation of the pre-hadron in the medium (absorption).

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Perturbative hadronization

In the energy loss scenario one assumes (ad hoc) that color neutralization always happens outside of the medium, $\boldsymbol{l_p \gg R_A}$

Perturbative hadronization

In the energy loss scenario one assumes (ad hoc) that color neutralization always happens outside of the medium, $l_p \gg R_A$

However, even in the string model this distance is not long, e.g. at $E_h = p_T = 10\,\mathrm{GeV}$ and $z = 0.7$,

$$l_p = \frac{E_h}{\kappa}(1 - z_h) = 3\,\mathrm{fm}$$

B.K. & F.Niedermayer (1983)

A.Bialas & M.Gyulassy (1987)

Dissipation of energy by a highly virtual quark is more intensive, therefore l_p should be even shorter.

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p_T broadening in DIS

The mean pathlength of a hadronizing quark in nuclear medium can be directly measured via $\boldsymbol{p_T}$-broadening:

$$\langle \boldsymbol{l} \rangle = \frac{\boldsymbol{\Delta \langle p_T^2 \rangle}}{\boldsymbol{z^2\, \hat{q}}}$$

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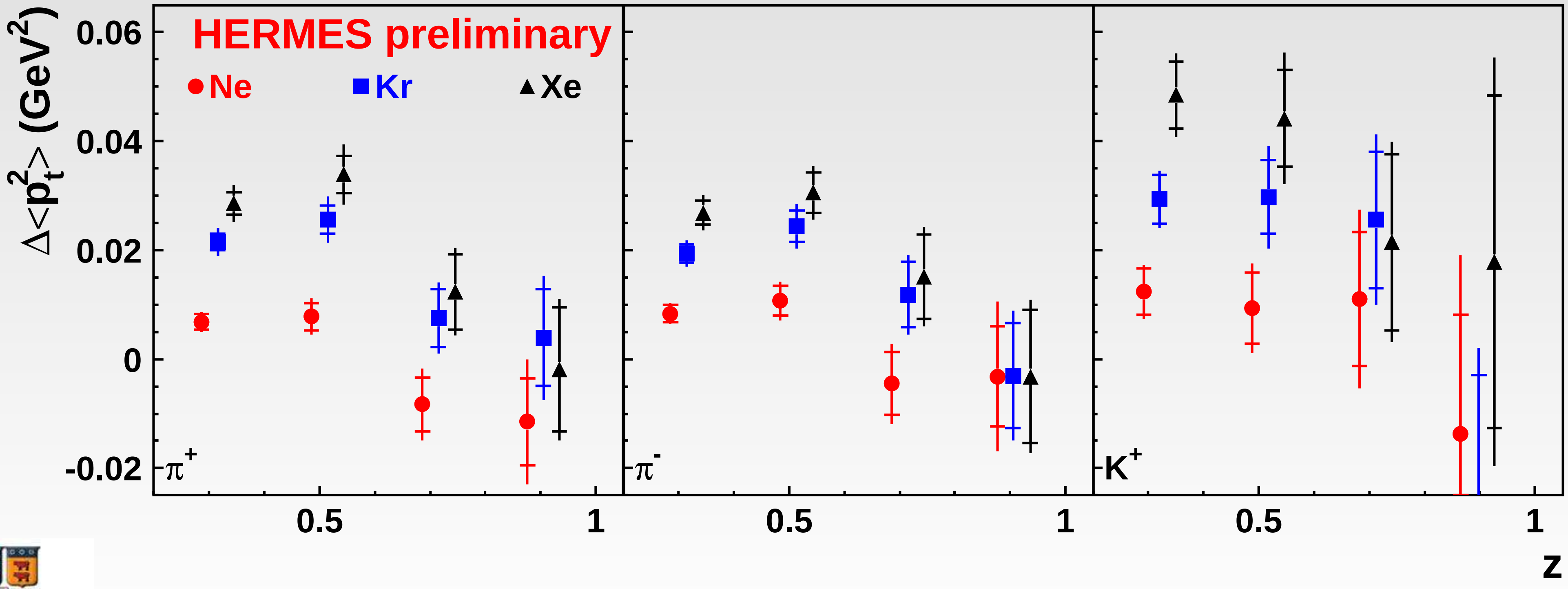

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p_T broadening in DIS

There is a consensus between different sources of information about the transport coefficient $\hat{q}$ in nuclei.

	Dipole 10 - 20 GeV	BDMS -	Drell-Yan 200 - 800 GeV	Cronin 200 - 800 GeV
$\hat{q}$ (GeV^2/ fm)	0.042	0.045	0.026 - 0.056	0.033 - 0.037

Thus, the mean pathlength of the quark in $\boldsymbol{Kr}$ and $\boldsymbol{Xe}$ at $\boldsymbol{z = 0.7}$ and $\langle \boldsymbol{\nu} \rangle = \mathbf{13.4}\,\mathrm{GeV}$ is very short:

$$\langle \boldsymbol{l} \rangle \approx \mathbf{0.6 \pm 0.4}\,\mathrm{fm}$$

- Absorption of the produced prehadron plays key role in quenching of pions produced in DIS off nuclei.

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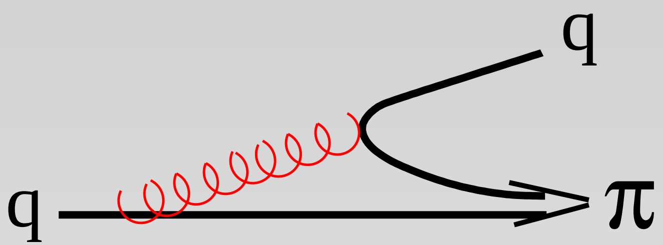
Time evolution of a high-p_T jet

Born approximation for the fragmentation function

$$\frac{\partial D_{q/\pi}(z,k)}{\partial k^2} \propto \frac{1}{k^4}\, z^2(1-z)^2$$



E.Berger (1979)

Changing the variable to

$$l_c = \frac{2z(1-z)E}{k^2}$$

one gets a constant distribution over pion production length,

$$\frac{\partial D_{q/\pi}(z,l_c)}{\partial\, l_c} \propto z(1-z)$$

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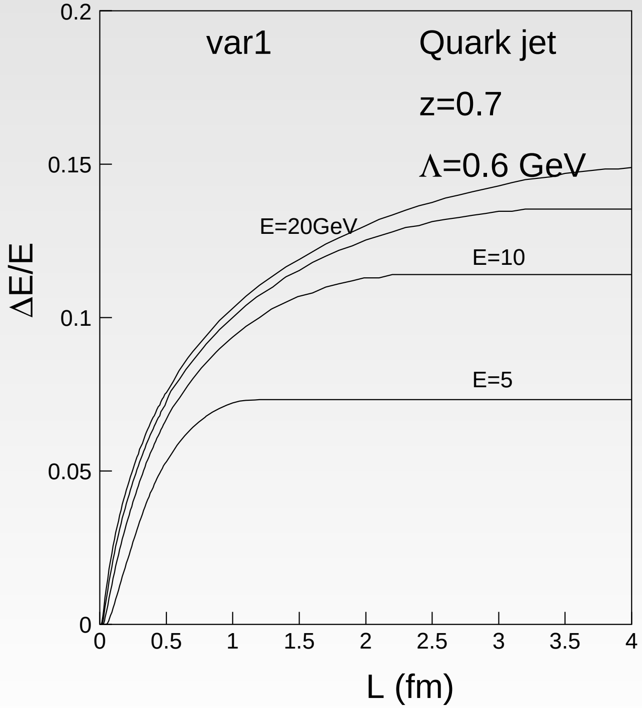
Time evolution of a high-p_T jet

The produced high-p_T "bare" quark has no field with transverse frequencies $k < p_T$. It can be expanded over Fock states containing different number of gluons, which are radiated in accordance with their coherence times. The quark has lower energy in higher Fock components, correspondingly, the fractional pion momentum should be redefined:

$$z \Rightarrow \tilde{z}(l) = z[1 + \Delta E(l)/E],$$

where $E \approx p_T$ is jet energy; $\Delta E(l)$ is vacuum energy loss.
To respect energy conservation only gluons with $\omega < E(1-z)$ are taken into account computing $\Delta E(l)$.



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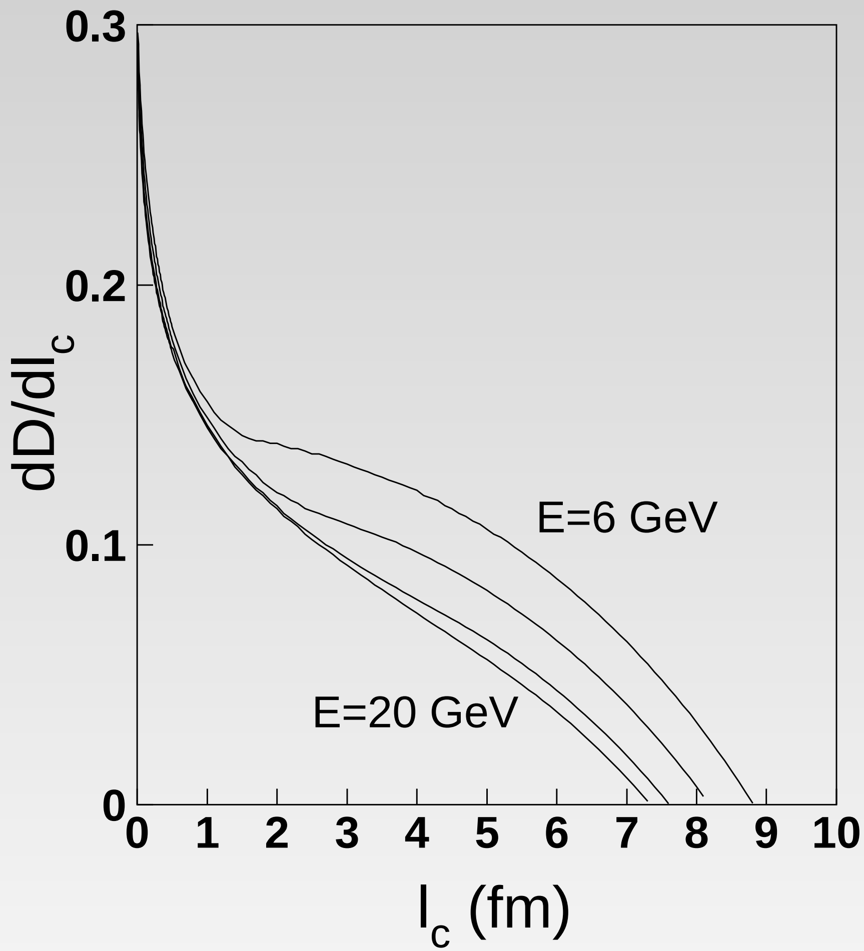
Time evolution of a high-p_T jet

The rest nonradiated gluons produce Sudakov suppression,

$$S(z,l) = e^{-\langle n_g(z,l)\rangle}$$

The l_c distribution of pions is modified by gluon radiation,



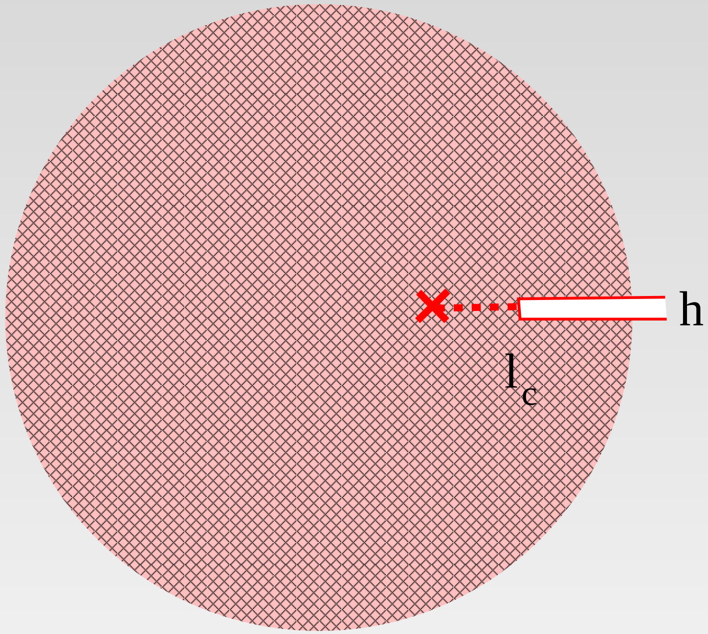
$$\frac{\partial D_{q/\pi}(z,l_c)}{\partial\, l_c} \propto \; \tilde{z}(l_c)[1-\tilde{z}(l_c)]\, S(z,l_c)$$

Quenching of high-p_T hadrons

For central collision of nuclei with constant density,

$$R_{AA} = \frac{\langle l_c^2 \rangle}{R_A^2} \left[1 - A \, \frac{L}{\langle l_c \rangle} + B \, \frac{L^2}{\langle l_c^2 \rangle} \right]$$

$$A \approx 0.15; \;\; B \approx 0.63$$



The effective absorption length,

$$L^3(E) = \frac{3E}{8 R_A \rho_A^2 X}$$

X is a parameter proportional to the medium density which is supposed to be fitted to data for R_{AA}.

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Quenching of high-p_T hadrons

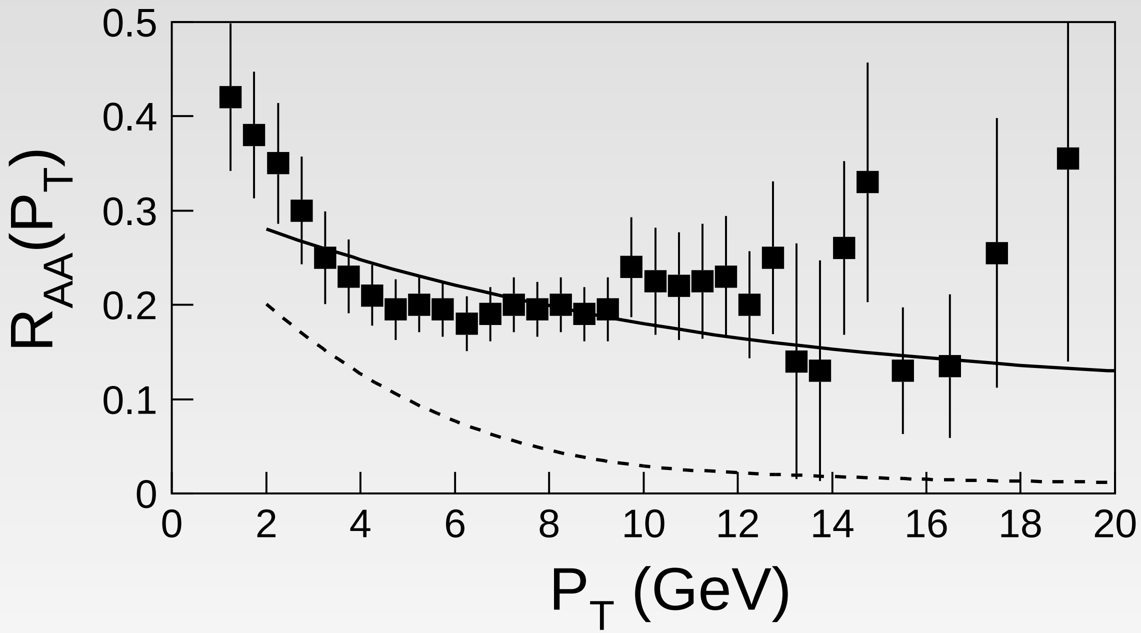
The prehadron dipole is produced with a rather large starting separation,

$$\langle r_T^2 \rangle \approx \frac{2\langle l_c \rangle}{zE} + \frac{1}{E^2}$$

At $E_\pi = zE = 10\,\mathrm{GeV}$ the initial size is $r_T \sim 0.3\,\mathrm{fm}$.

For such a large dipoles the mean free path in a dense medium is vanishingly small. Neglecting $L \ll \langle l_c \rangle$ we arrive at a simple result,

$$R_{AA} = \frac{\langle l_c^2(p_T) \rangle}{R_A^2}$$



R_{AA} is independent of the medium density and can be predicted

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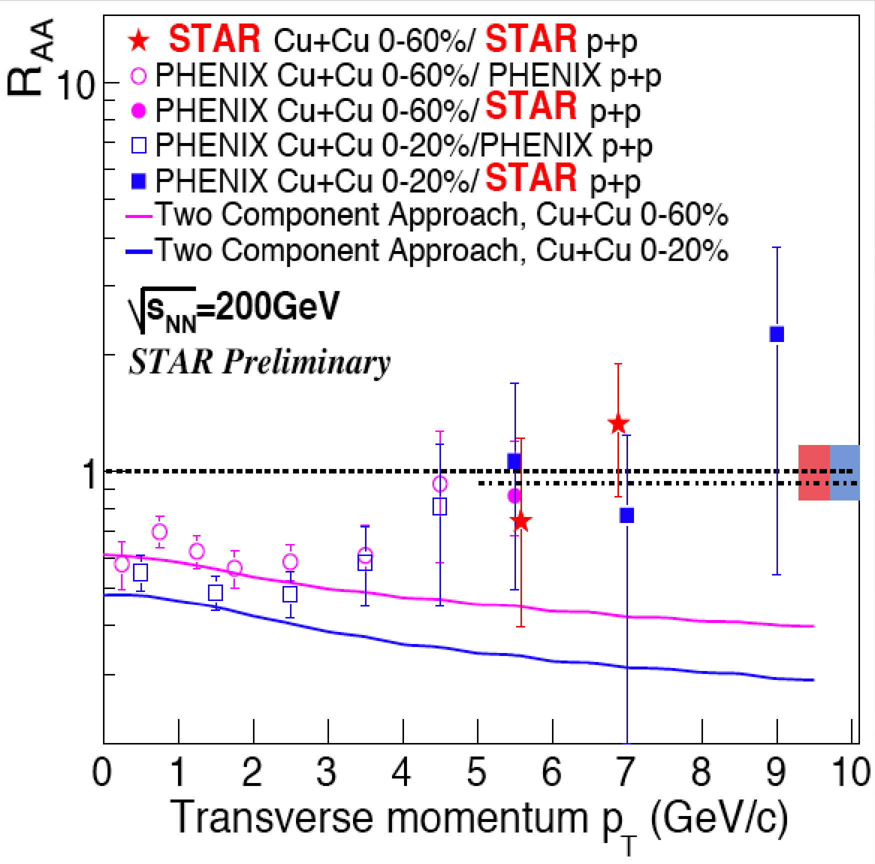
Quenching of J/Ψ

I a very dense matter a J/Ψ at large p_T should be suppressed as much as other hadrons. This does not seem to be the case.



If this is true, then it might indicate that the density is not sufficiently high, and the mean free path of a $\bar{c}c$ dipole rises with p_T due to color transparency.

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Summary

- The original hope that one can measure charmonium-nucleon cross section at low energy in pA collisions at $x_F < 0$ failed. Cascading gluons radiated in the Bethe-Heitler regime in the nuclear fragmentation region enhance production of charmonia, open heavy flavor and any hard reaction. This effect scales in x_F.

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- In the central rapidity region of small x_F, shadowing affects the production of heavy flavors, provided that x_2 is sufficiently small. Shadowing contains a leading twist (gluon shadowing) and higher twist (quark shadowing) components. Heavy quarkonia are additionally suppressed by absorption which is controlled by color transparency effects. All these effects scale in x_2.

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Summary

- At large $x_F \longrightarrow 1$ additional suppression comes from the energy sharing problem, which can be represented as an energy loss which is proportional to energy. This suppression scales in x_F. Higher and leading twist shadowing contribute as well, if the coherent length is sufficiently long.

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Summary

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- There are many experimental and theoretical facts favoring a short hadronization time, which leads to hadron creation mainly within the medium. Attenuation of the (pre)hadrons is a stronger effect than energy loss and should be similar for different hadronic species, light or heavy flavored. In the limit of high density R_{AA} saturates at a density-independent value which can be evaluated within models.